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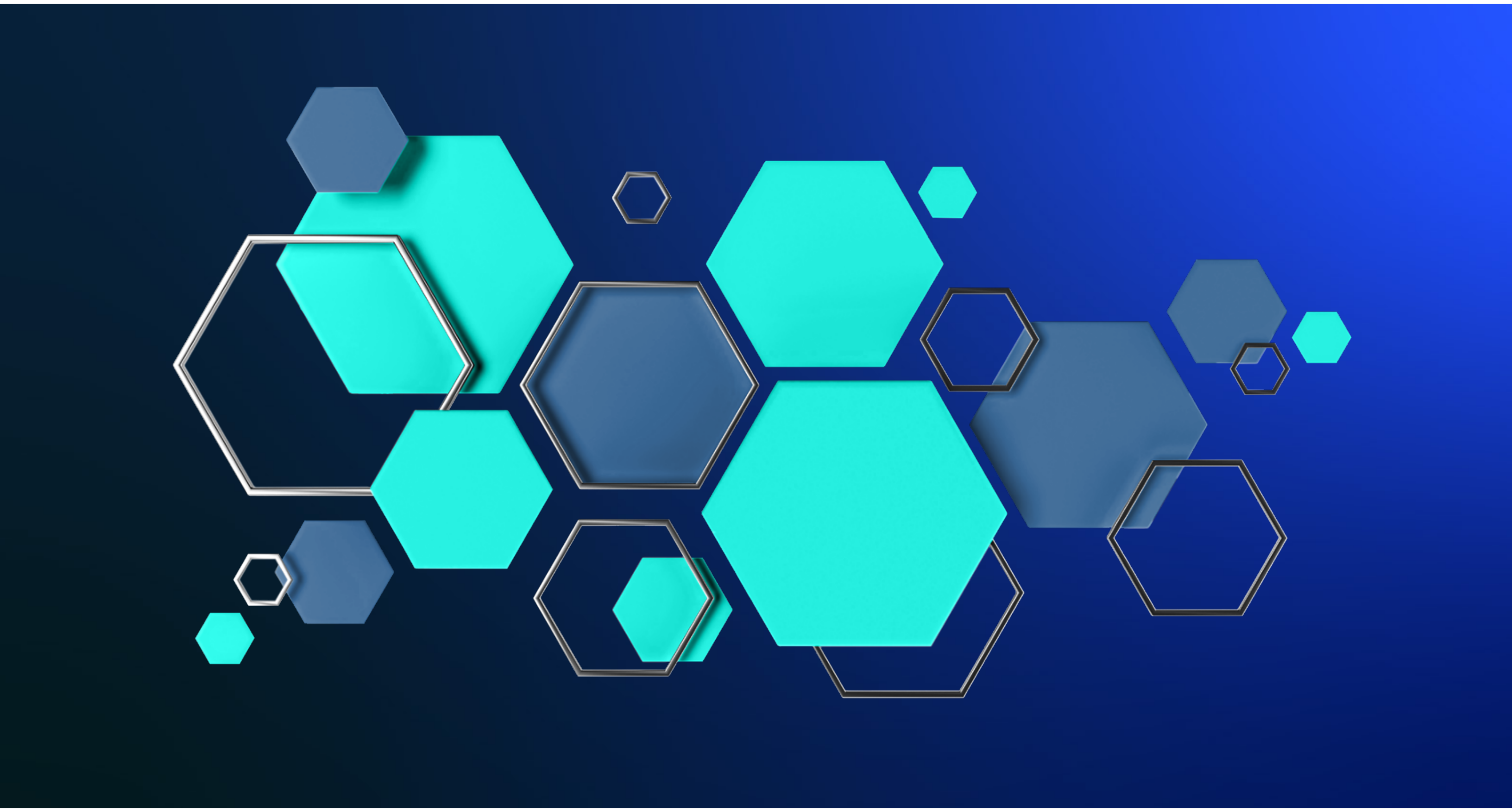
The hard stuff 2025: Taking stock of progress on the physical challenges of the energy transition

The energy transition is proceeding, but unevenly. Easier challenges are being solved, but harder ones are stalling.



November 2025

At a glance

— **The physical transformation needed for the energy transition is advancing, but at about half the pace required to meet global commitments.** Less than 15 percent of the low-emissions technologies required to meet Paris-aligned targets by 2050 have been deployed—a few percentage points higher than two years ago.

— **Deployment advanced in three of the seven parts of the energy system but stalled elsewhere.** Momentum is strongest in low-emissions power, electrifying transportation, and critical mineral supplies. Progress is mostly stuck in carbon capture, hydrogen fuels, and heavy industry.

— **China accounts for about two-thirds of additional solar and wind power and electric vehicle sales since 2022.** Emerging economies have stepped up, but the pace of deployment in the United States and the European Union slowed in 2025 in some areas.

— **The outlook has worsened for the hardest physical challenges of the transition.** Advancing the transition will require tackling 25 physical challenges. There are bright spots such as improved range for electric vehicles. But progress on the most demanding challenges, including those related to hydrogen and decarbonizing steel, has been hampered by project cancellations, slow technological progress, and policy shifts.

— **Understanding the physical realities of the energy transition is more important than ever.** This lens clarifies the scale of the task ahead, helping to set priorities amid uneven progress and to pinpoint emerging areas of opportunity and bottlenecks that demand new approaches.

Today's energy system, encompassing the production and consumption of energy resources, is high performing, deeply enmeshed in the global economy, and has developed over centuries. But for all its advantages, today's system also has flaws, most notably the fact that it generates more than 85 percent of global emissions of carbon dioxide (CO_2).[1]

Stakeholders around the world are engaged in the task of transforming the system to reduce its emissions. There is growing recognition that this must be done in a way that is affordable, reliable, enables competitiveness, and, in many places in the world, while increasing overall access to energy.[2] More recently, a shifting policy landscape, geopolitical tensions, and surging energy demand from data centers have added further complexity.

In a digital age, we have become accustomed to lightning-fast transformations. However, the energy transition, particularly one that enables these broader objectives, is a challenging undertaking and requires a vast and complex physical transformation.

In 2024, the McKinsey Global Institute's report *The Hard stuff: Navigating the physical realities of the energy transition* took stock of where the world stands on this physical transformation. We found that, despite meaningful progress, the transition was in its early stages, with just about 10 percent of the required deployment of low-emissions technologies by 2050 achieved in most areas.[3] The research identified 25 physical challenges that must be overcome for the transition to succeed—from developing and scaling new low-emissions technologies to building the supply chains and infrastructure they depend on.

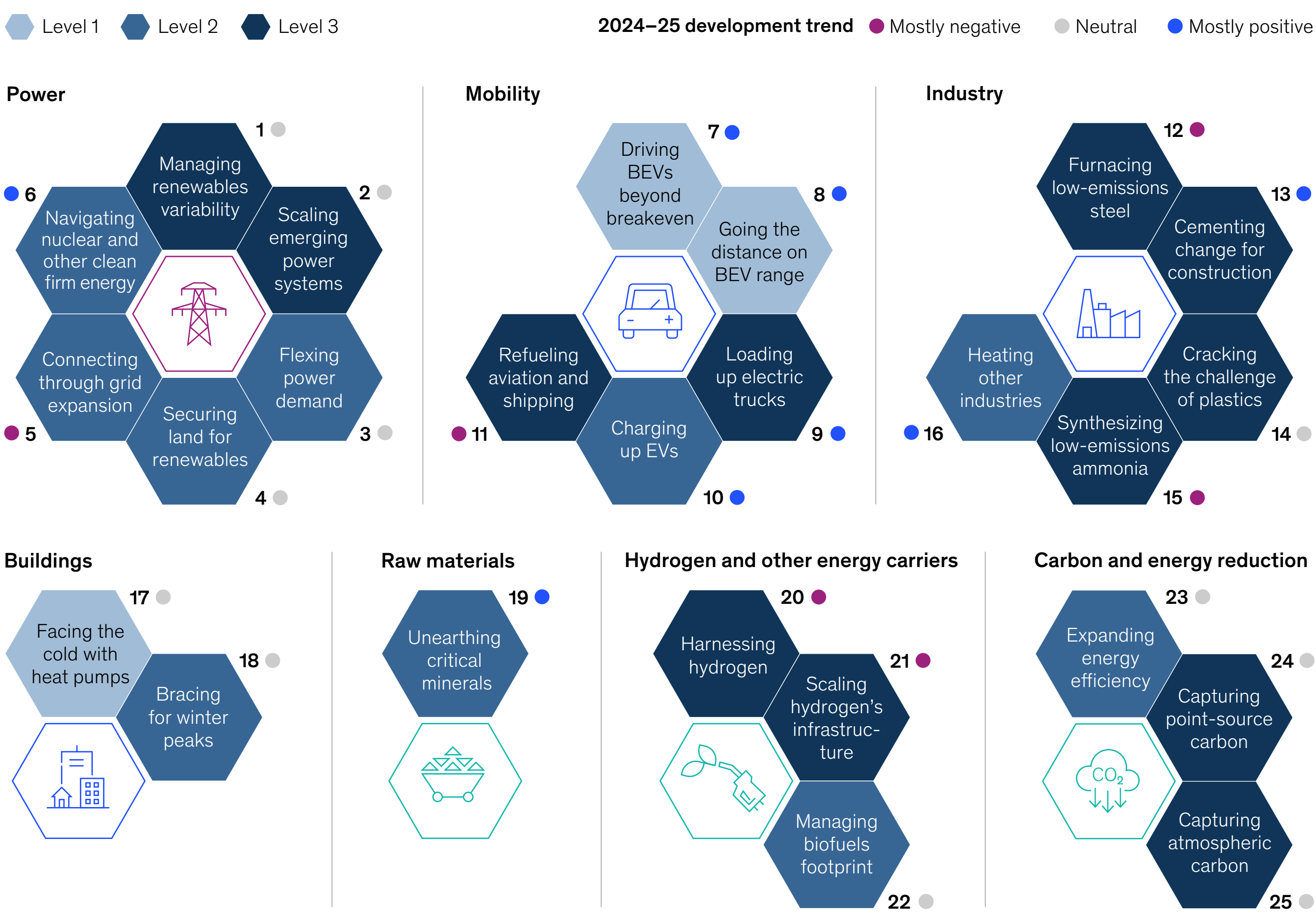
We grouped the 25 physical challenges into three levels of difficulty. Level 1 challenges require progress on deploying established technologies and face the fewest physical hurdles. Level 2 challenges require accelerating deployment of known technologies, along with scaling the associated infrastructure and inputs. In Level 3 challenges—we call these 12 the "demanding dozen"—gaps in technological performance remain (often in demanding use cases), large interdependencies exist, and the transformation is just beginning.

In this research, we update our assessment of the energy transition with another reality check on where things stand, where progress has been made, and the task ahead. We find that an estimated 13.5 percent of the deployment to meet Paris-aligned goals has now been done. Many factors have driven progress on deployment across regions where it has occurred—emissions reduction goals, but also favorable economics, and the broader imperatives that we have noted.[4] Nevertheless, progress has proceeded at roughly half the pace that would have been required to meet targets aligned with the 2015 Paris Agreement, with only a few percentage points of headway in two years.

Against this backdrop, we find a tale of many transitions (Exhibit 1). Deployment has taken place, but it has largely involved only critical minerals, low-emissions power, and electric vehicles (EVs). There has been little movement in hydrogen, carbon capture, or low-emissions technologies for making steel and other key materials.

Exhibit 1

The 25 physical challenges identified in 2024.



Source: McKinsey Global Institute analysis

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China accounted for about two-thirds of recent deployment in EVs and in solar and wind power.[5] In the first half of 2025, emerging economies (excluding China) installed more new solar and wind capacity than either the European Union (EU) or the United States, where momentum is slowing.

And what of progress on the 25 challenges that will need to be tackled for the energy transition to succeed? The picture is mixed. Many of the easier challenges are getting solved, but we remain stuck on the most demanding ones, particularly related to improving performance and affordability.

Our aim with this research is to help business leaders and policymakers identify where there is opportunity from the energy transition and where fresh ideas are needed.

The transition is moving at half the pace needed to meet Paris-aligned targets

The energy transition is moving forward, but unevenly. Deployment of solar panels, batteries, and electric cars has been accelerating, for example. Similarly, the supply of critical minerals is rising quickly as new facilities come online, so much so that there are worries of oversupply in the short term.[6] But progress in other areas—notably, decarbonizing heavy industries, scaling hydrogen, and capturing carbon—is largely stuck. Of the seven domains of the energy system we track, three are progressing and accelerating, but four are not.

By the end of 2024, about 13.5 percent of low-emissions technologies needed to meet Paris-aligned 2050 targets across the seven domains we study had been deployed on average.[7] This is about three percentage points of progress in two years. This pace is roughly half of what would be required to meet Paris-aligned targets. Six percentage points on deployment in the past two years would have been in line with such targets (Exhibit 2).

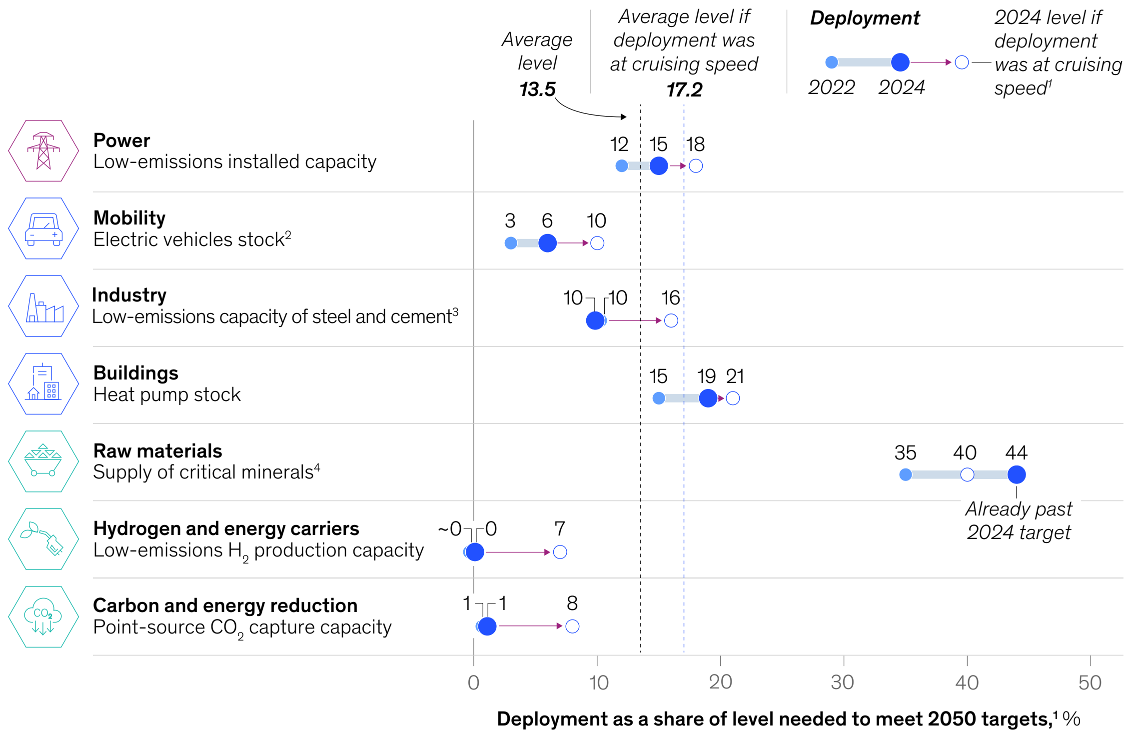
We also analyze how deployment is progressing in each domain by measuring it against a "cruising speed." By this, we mean a hypothetical constant speed of required annual deployment that is consistent with keeping global warming well below 2°C. While recognizing that progress may not be linear, this approach is a useful way to calibrate how we are going (for more on our approach, see sidebar "Measuring progress").[8]

Many of the easier challenges are getting solved, but we remain stuck on the most demanding ones, particularly related to improving performance and affordability.

Exhibit 2

The energy transition is advancing at half the required pace.

Deployment of low-emissions technologies, 2022 and 2024 actual and 2024 at cruising speed, % of total deployment required to meet 2050 targets[1]



[1]2050 targets refer to Paris-aligned targets using deployment in McKinsey's *Global energy perspective 2023* Achieved Commitments scenario that keeps global warming in 2100 within about 1.6°C relative to preindustrial averages. 2024 deployment at cruising speed refers to deployment in 2024 if annual additions in 2022–24 equal average annual additions in the Achieved Commitments scenario.
[2]Stock includes electric passenger vehicles, including battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid and range-extended electric vehicles (PHEVs/REEVs). All classes (cars, vans, trucks, buses) other than 2- and 3-wheelers included.
[3]Low-emissions production volumes fell in both 2022 and 2023. We do not have a 2024 estimate but conservatively assume that there was no increase in that year.
[4]The deployment ratio for raw materials was calculated with a three-step approach. First, we compute the ratio between supply level (2022, 2024, and at "cruising speed") and 2050 projected demand level for each material. Second, we calculate the average deployment ratio for rare earths (ie, dysprosium, neodymium, praseodymium, and terbium). Third, we calculate the overall deployment ratio for raw materials as the average between the deployment rates of rare earths, and that of each other material (ie, cobalt, copper, lithium, and nickel).
Source: International Renewable Energy Agency; International Energy Agency; McKinsey MineSpans; McKinsey Battery Insights; McKinsey Center for Future Mobility; Global energy perspective 2023, McKinsey; WorldSteel; McKinsey Global Institute analysis

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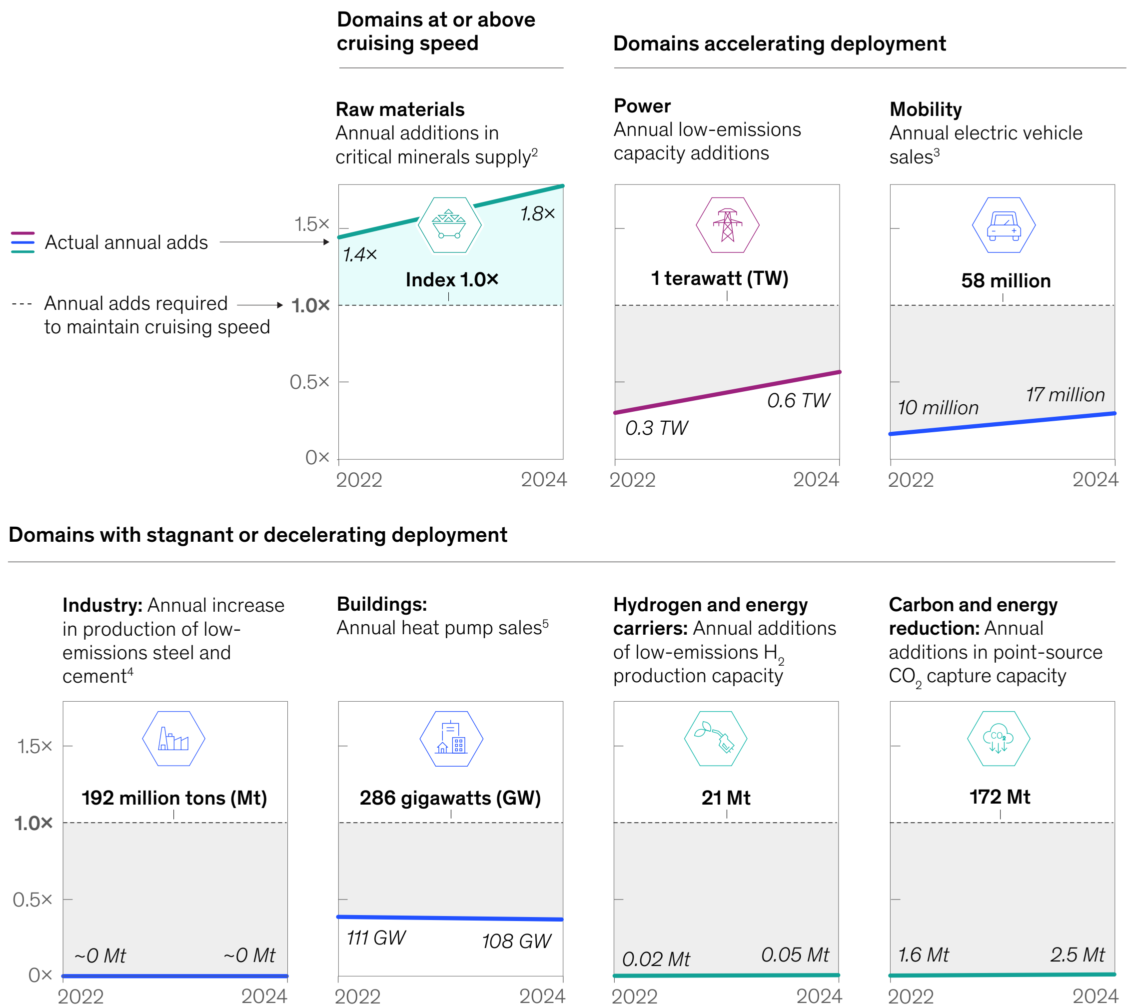
Among the domains, raw materials is the only one where progress is outstripping cruising speed (Exhibit 3). Supply of critical minerals has been growing, especially in Africa, China, and Indonesia. Higher investment and an acceleration in the time it takes to bring projects online have put critical minerals on a trajectory that can sustain rapid growth in solar, batteries, and EVs.[9]

Exhibit 3

Deployment accelerated in critical minerals, power and mobility globally, but stagnated elsewhere.

Annual capacity additions, 2022 and 2024 actual and 2024 at cruising speed[1]



[1]The pathway considered is McKinsey's Achieved Commitments scenario, which keeps global warming by 2100 within about 1.6°C relative to preindustrial averages. For all sectors except mobility and buildings, capacity additions are net (not accounting for the need to replace capacity at end of life). For mobility and buildings, capacity additions are annual sales.
[2]For a single index for added raw materials supply, we compute the annual supply change for 2022 and 2024 for eight minerals: copper, lithium, nickel, cobalt, neodymium, praseodymium, dysprosium, and terbium (the latter four are rare earths). For each mineral, we then compute the average annual change of supply required for an Achieved Commitments pathway. We divide the 2022 and 2024 supply additions by the annual supply additions on that pathway. These ratios are necessary to normalize additions across minerals. We then compute an average of the ratio of additions for rare earths only. Last, we compute an average ratio of additions for copper, lithium, nickel, cobalt, and rare earths.
[3]Annual adds consider sales of electric passenger cars, including battery electric vehicles (BEVs), fuel cell vehicles (FCEVs), and plug-in hybrid and range-extended electric vehicles (PHEVs/REEVs).
[4]Measuring capacity additions (not cumulative capacity) for primary and secondary production. Low-emissions production volumes fell in both 2022 and 2023. We do not have a 2024 estimate but conservatively assume that there was no increase in that year. The 2050 target is computed by adding required adds for cement and steel.
[5]For heat pumps the required annual adds at cruising speed are the average of 2022 sales and 2050 projected sales on the Achieved Commitments pathway.
Source: International Renewable Energy Agency; International Energy Agency; McKinsey MineSpans; McKinsey Battery Insights; McKinsey Center for Future Mobility; *Global energy perspective 2023*, McKinsey; WorldSteel; McKinsey Global Institute analysis

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Power is also in high gear. Between 2022 and 2024, annual additions of solar, wind, and other low-emissions generation doubled to 600 gigawatts, almost as much as the combined power grids of India and Brazil.[10] Momentum on capacity additions further strengthened in early 2025, with wind and solar collectively up more than 60 percent year on year. The vast majority of these additions were of solar capacity. To put this into perspective, more solar capacity has been added since 2022 than in all previous years.[11] If the pace holds, global capacity additions could reach a cruising speed of about 1,000 gigawatts of new low-emissions power annually before 2030.

Sidebar

Measuring progress

This research assesses the state of the energy transition, and recent advances. It examines the global stock and additions of low-emissions technologies in 2024 and compares them with levels recorded in 2022.

We express deployment as a percentage of what would be required by 2050 to meet the aim of the 2015 Paris Agreement—namely, "holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels."[1]

This approach of comparing current deployment relative to that in 2050 is a helpful indication of the transformation accomplished to date, the progress of the energy transition, and the scale of future transformation needed. But there are caveats. Some of today's low-emissions stock of assets may not exist by 2050; some assets may have life cycles of ten or 15 years and will need to be replaced. And some of today's high-emissions assets will naturally turn over between now and 2050 as they reach the end of their useful life. Moreover, the energy system is expected to grow, and some of the deployment required in 2050 is driven by growth and not solely by the substitution of existing low-emissions assets. Nonetheless, it is a helpful gauge of where the world stands on the energy transition and the pace of progress.

Our benchmark for 2050 deployment is McKinsey's 2023 Achieved Commitments scenario, which assumes that countries deliver on their pledges to reach net-zero emissions (by 2050 in most but not all cases), resulting in warming of about 1.6°C relative to preindustrial levels by 2100.[2] We use this scenario because it provides detailed, technology-by-technology data for year-on-year tracking. We previously compared it with other "fast transition" pathways such as those of the International Energy Agency's (IEA) Net Zero and BloombergNEF Net Zero and found that their conclusions were broadly similar.

Of course, commitments have changed in the past two years, but we have continued to use this scenario as our benchmark for two reasons. First, it allows us to compare progress against an ambitious, Paris-aligned target. Second, it was the scenario we used in our 2024 research, and this enables us to be consistent in measuring progress on deployment, avoiding changing the baseline.

Data sources used for this analysis include the International Energy Agency (IEA), McKinsey's *Global energy perspectives*, the McKinsey Center for Future Mobility, the International Renewable Energy Agency (IRENA), and the International Atomic Energy Agency (IAEA).[3] Among the external sources of data used in this report, we acknowledge the use of publicly available data from the IEA (Paris) and several IEA sources, including *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach* (IEA, September 2023) and *Global critical minerals outlook 2025* (IEA, May 2025). All are licensed CC BY 4.0.

We note that some of our analysis draws on IEA material, but MGI is solely liable and responsible for the contents of this paper; they are not endorsed by the IEA. This is true for all providers of data in this analysis. We gratefully acknowledge their input, but the conclusions and any errors are our own.

1 The Paris Agreement, United Nations, 2015.
2 The 2023 Achieved Commitments scenario is explored in *Global energy perspective 2023*, McKinsey, October 2023. The Paris Agreement sets the global goal ("well below 2°C, ideally 1.5°C") but doesn't specify a detailed deployment trajectory. McKinsey's Achieved Commitments scenario translates the country-level pledges formulated prior to October 2023 into a quantitative pathway—by technology and geography—that we can use for year-to-year measurement.
3 Key reports and data sets from the IEA include the 2024 Renewable Energy Progress Tracker, *World energy outlook 2024*, *Global EV outlook 2025*, *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach* (September 2023), *Global critical minerals outlook 2024*, the Hydrogen Production and Infrastructure Projects Database, and the CCUS Projects Database. The key IRENA source we used was Renewable Capacity Statistics for 2025, © IRENA 2025.

Mobility is another bright spot. By mid-2025, about one in four passenger cars sold worldwide was electric. Global sales of battery electric and plug-in hybrid cars reached 17 million in 2024, up 70 percent from 2022, and momentum carried into 2025. Still, a reality check is in order: Volumes would need to more than triple, to around 60 million a year, for this domain to reach cruising speed.[12]

In the other domains—buildings, industry, hydrogen, and carbon management—the story is far less encouraging. Although sales of heat pumps are above prepandemic levels, the surge in deployment of heat pumps after Europe's 2022 gas price shock has receded.[13] In the other three domains, deployment remains negligible.

Even in the accelerating domains of power, mobility, and raw materials, it is certainly too soon to declare victory on their ability to reach cruising speed. There are two important caveats. First, so far, China has driven the lion's share of progress. If these domains are to keep growing and reach their cruising speed, progress will have to be more global. Second, as we discussed in our 2024 report, as deployment advances, it can become harder. For example, as more renewables are introduced into power generation, the system can become more volatile.

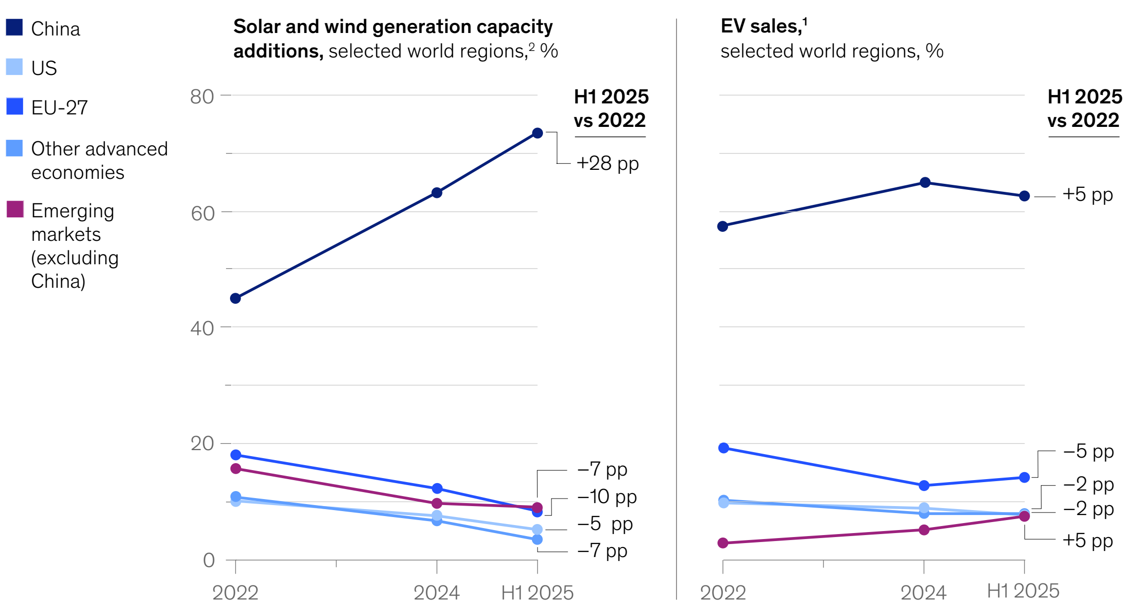
The next two chapters examine precisely these two aspects: regional differences and the physical challenges that need to be tackled for the energy transition to succeed.

China accounts for two-thirds of deployment, but emerging economies are stepping up

The geography of deployment in the energy transition is also not even and is shifting. China sits at the front, emerging economies are moving faster, and deployment in advanced economies is slowing down in some areas. In the domains that are accelerating, notably power and mobility, China has been responsible for around two-thirds of deployment in recent years (Exhibit 4).

Exhibit 4

China remains the key driver of additions of low-emission technologies, and emerging markets are increasing their role.



[1]Passenger cars including battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and range-extended electric vehicles (REEVs).
[2]Analysis based on Ember data for 25 countries, accounting for ~89% of global and solar and wind generation capacity as of end 2024.
Source: Ember; International Energy Agency; McKinsey Center for Future Mobility; McKinsey Global Institute analysis

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China is playing the largest role globally in deploying low-emissions technologies

China is the world's largest emitter of CO_2 and has also accounted for most increases in emissions since 2022.[14] Fossil fuels provide about 87 percent of China's energy supply, and its electricity grid is still heavily reliant on coal and other fossil fuels for more than 60 percent of generation.[15]

Nonetheless, China also accounts for the most progress in the deployment of low-emissions technologies. Since 2022, China has delivered nearly two-thirds of all new global capacity of solar and wind power. In the first half of 2025, this figure reached three-quarters. This boom now gives China almost a quarter of the low-emissions power needed to meet its share of 2050 deployment targets—nearly double the global average.

China's role in mobility is just as notable. China accounts for six out of ten passenger EVs and nine out of every ten electric trucks on the road. In the first half of 2025, passenger EVs sold in China accounted for almost 65 percent of global sales. China has already reached 19 percent of the EV deployment needed by mid-century, compared with just 3 percent elsewhere.[16]

Momentum in the United States and Europe slowed in 2025

In 2024, the United States added about 40 gigawatts of solar and wind capacity, a 60 percent jump from 2022 additions. But in the first half of 2025, new additions were flat compared with the same period in the previous years. EV sales also hit a plateau after years of rapid growth.[17]

In Europe, deployment is also advancing at a slower pace in some areas. The EU added about 70 gigawatts of solar and wind in 2024—a 40 percent increase relative to 2022—but as in the United States, there hasn't been any year-on-year growth in 2025. By contrast, EV adoption continued to climb, with passenger EV sales up more than 20 percent in the first half of 2025, compared with a year earlier.[18]

Nevertheless, progress on deployment can be found within each of these regions. For instance, in the United States, some states moved ahead faster. While installations of solar power in the United States overall were up by less than 5 percent in the first six months of 2025, compared with a year earlier, several states, including Arizona, Georgia, Ohio, and Texas, grew installations by 15 to 80 percent.[19] A similar picture played out in the EU, where Spain and France increased the solar and wind capacity installed by around 35 and 25 percent, respectively.[20]

Emerging economies stepped up deployment

Perhaps the most striking development has been the increased role of deployment of low-emissions technologies in emerging economies. Since 2022, the additions of solar and wind power have grown faster than in the United States or the EU. In fact, in the first six months of 2025, emerging economies installed an estimated 30 gigawatts, similar to the EU. India alone added more than 20 gigawatts—more solar and wind power than the United States during that period.

Much of this momentum has been fueled by Chinese exports. Solar exports to emerging economies doubled from 2022 to 2024, overtaking those to high-income economies.[21] Brazil, India, Pakistan, and Saudi Arabia have emerged as leading importers while demand across Africa has also surged.[22] The growth of distributed generation (for example, solar panels installed on the rooftops of people's homes) is a big driver, helping extend access in markets where central grid expansion is slower.[23]

EV adoption in emerging markets is also accelerating. Between 2022 and 2024, their share of global EV car sales almost doubled, from about 3 percent to 5 percent. In the first half of 2025, the number increased to 7 percent—roughly equal to the US total. The growth has been striking in economies like Brazil, where sales jumped from about 20,000 in 2022 to more than 120,000 in 2024, and in Southeast Asian countries, where sales grew from around 40,000 to more than 200,000 in the same period, a fivefold rise.[24]

The hardest stuff may be getting harder

While progress has been achieved in deploying low-emissions technologies, the transition remains in its early stages, and progress is far from even. Achieving the remainder of the energy transition will require addressing 25 physical challenges, as outlined in our 2024 report. Examples of physical challenges are managing power systems with a large share of variable renewables, addressing range and payload challenges in electric trucks, and finding alternative heat sources, feedstocks, and processes for producing industrial materials.

In 2024–25, we find that many of the (relatively) easy physical challenges are being solved, but the hardest ones remain broadly stuck. Since 2022, almost no progress has been made on the demanding dozen. However, about half of energy-related emissions depend on tackling these challenges (Exhibit 5).

Exhibit 5

Level 3 challenges face the strongest headwinds.

Number of challenges by level and 2024–25 trend

Mostly negative · Neutral · Mostly positive

Level	Mostly negative trend	Neutral trend	Mostly positive trend
1		*1 challenge* **17** Facing the cold with heat pumps	*2 challenges* **7** Driving BEVs beyond breakeven **8** Going the distance on BEV range
2	*1 challenge* **5** Connecting through grid expansion	*5 challenges* **3** Flexing power demand **4** Securing land for renewables **18** Bracing for winter peaks **22** Managing biofuels footprint **23** Expanding energy efficiency	*4 challenges* **6** Navigating nuclear and other clean firm energy **10** Charging up EVs **16** Heating other industries **19** Unearthing critical minerals
3	*5 challenges* **11** Refueling aviation and shipping **12** Furnacing low-emissions steel **15** Synthesizing low-emissions ammonia **20** Harnessing hydrogen **21** Scaling hydrogen's infrastructure	*5 challenges* **1** Managing renewables variability **2** Scaling emerging power systems **14** Cracking the challenge of plastics **24** Capturing point-source carbon **25** Capturing atmospheric carbon	*2 challenges* **9** Loading up electric trucks **13** Cementing change for construction

Source: McKinsey Global Institute analysis

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Easier challenges are being solved
In this update, we found that the 13 challenges previously categorized as Level 1 and 2 remained in those categories. But many of them continue to experience forward momentum. There has been progress in the form of continued technological improvement and removal of bottlenecks to help with scaling in six of them since our 2024 report.

Most progress was in electrification-related areas and improvements in underlying technologies. Batteries are a prime example. Their energy density has improved 10 to 20 percent across different chemistries, which has extended the range of EVs (challenge 8).[25] Furthermore, the increased use of chemistries such as lithium iron phosphate (LFP) has led to the reduction in both emissions from manufacturing and the cost of manufacturing EVs, improving the breakeven distance of EVs in comparison with internal combustion engine (ICE) vehicles in terms of their carbon (and cost) savings (challenge 7).[26]

Having sufficient clean firm power as a complement to variable renewables (challenge 6) has also progressed. While deployment of clean firm power has not advanced meaningfully since 2022, new technologies promise to create new options even if they are a few years away from mass commercialization. Geothermal drilling times have fallen by about 80 percent; pilots for enhanced geothermal systems have launched in the United States; and a few small modular reactors (SMRs) are actively under construction, including in Argentina, China, Russia, and the United States, with more than 30 in the design stage.[27]

That is the good news, but of the comparatively easy Level 1 and 2 challenges, there are still six where progress has, on balance, been neutral, often with both positive and negative developments.

And in one case, the negatives outweighed the positives. The grid is a growing bottleneck (challenge 5). Supply chain constraints have pushed transformer and cable prices up by about a third since 2022, while delivery times have doubled to two or three years.[28] At the same time, the IEA has estimated that 1,650 gigawatts of solar and wind capacity globally were awaiting connection in 2024, due to grid investment and permitting delays. That is equivalent to six times Germany's current generation capacity.[29] Expanding the grid is critical to the entire transition to, for instance, support the connection of new low-emissions power sources, integrate storage, and enable EV charging.

Overall, policy has had a mixed impact on the pace of the transition. In the case of Level 1 and Level 2 challenges, policy measures did offer some tailwinds. One example is reforms to nuclear permitting that streamline approvals for early-stage projects, including advanced reactor designs (challenge 6).[30] In Europe, recent initiatives streamlined permitting to secure critical mineral supplies (challenge 19) and expanded support for heat electrification (challenge 16).[31]

But for the hardest—Level 3—challenges, the picture looks meaningfully different.

Level 3 challenges are mostly stuck, despite a few bright spots
Solving Level 3 challenges requires meaningful technology advances, establishing a track record of deployment to build scale, and solutions to complex interdependencies. However, during the past two years, the opposite has occurred for many Level 3 challenges. Attempts to tackle five of the demanding dozen challenges are mostly experiencing negative trends.

Across these five, of course there has been some innovation, such as the emergence of new types of hydrogen electrolyzers and new processes for producing industrial materials. However, by and large, more effort is needed to improve performance and costs in these areas. Moreover, a deteriorating economic background together with policy shifts (some in 2025) have prompted the cancellation of many of the few pilot projects that had been underway. So, progress toward commercial scale has been negligible (see sidebar "New forces are reshaping the transition").

Sidebar

New forces are reshaping the transition

New forces have affected the evolution of the energy landscape and transition in 2024–25 and may continue to do so.

In the United States, the One Big Beautiful Bill (OBBB) Act rolled back or accelerated the phase-out of incentives for renewable and low-emissions energy technologies, especially wind and solar power, low-emissions hydrogen, and EVs; while expanding support for the extraction of critical minerals, the production of some categories of low-emissions fuels, and some uses of carbon capture.

How exactly this affects low-emissions technologies remains uncertain but could be quite varied. In the case of power, the OBBB Act could well cause a brief spike in wind and solar commissioning in 2025–26 (projects being brought forward prior to the phaseout of subsidies). This could be followed by slower, but still positive, growth after that. Analysts, for example, estimate that overall solar and wind deployment up to 2030 could double relative to 2024 but would be around 30 percent lower than it would have been under previous policy settings.[1]

In the case of EVs, the impact of the OBBB Act on sales could be larger. Analysts have estimated that the share of EVs in total car sales in the United States by 2030 could be only about 25 percent, roughly half of previous projections.[2] In the case of hydrogen, by contrast, many projects were already losing steam before the OBBB Act. Project final investment decisions (FIDs) and the global pipeline had begun to contract amid cost and market uncertainty.[3]

Elsewhere, policy settings have also shifted. The EU launched investment incentives through the Clean Industrial Deal and tightened energy-saving targets, yet several member countries reduced policy support for solar, EVs, and heat pumps.[4] China advanced its climate and energy policy by establishing a unified electricity market for renewables under the 2024 Energy Law and by approving the expansion of the national emissions trading system to high-emitting industries, such as cement, steel, and aluminum.[5]

Geopolitics added further complications. While there is much uncertainty, McKinsey estimates suggest that tariffs could lead to marginally slower growth of installations of solar and wind in the United States and the EU—6 percent slower by 2035, but still corresponding to a more than doubling of 2024 capacity. This could mean that energy system costs could be approximately 2 to 3 percent higher than they would have otherwise been.[6] There are second-order effects to consider, too. If tariffs shift China to direct excess production to other regions at lower prices, deployment would be faster elsewhere.

Perhaps most uncertain is the impact of a potential acceleration in the deployment and use of artificial intelligence (AI) technologies. A rise in data center announcements in 2025 raised concern about a spike in electricity demand from this source. This may be less relevant at a global level. In most scenarios, data centers are expected to grow quickly, but their demand for power is expected to remain limited at roughly 5 percent of global electricity use—lower than demand from air conditioning, for instance.[7] But demand load from data centers could be especially high in hot spots where grid capacity is already under strain. In the United States, for example, data centers could account for as much as 15 percent of electricity demand by 2030. But while data centers may put strain on the grid, they also create opportunities. Although the hunger for energy to support rising data center demand has been in part powered by fossil fuels, it has also created positive tailwinds for solar plus storage and some sources of clean firm power. This could continue in the future, especially since well-capitalized technology firms may be able to pay premiums for low-emissions power.[8] Furthermore, data centers may soon be a new source of demand-side flexibility.[9]

We should also anticipate that these forces will interact with each other. For instance, more demand for power from data centers could incentivize new renewables projects; new OBBB Act provisions could reduce them. This could play out very differently among regions and technologies, strengthening the argument in favor of maintaining a granular understanding of how the energy transition is playing out and how physical challenges are likely to be addressed.

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1 Different analysts find slightly different results depending on previously assumed scenarios, but impacts are overall consistent. See, for example, Rapid Energy Policy Evaluation and Analysis Toolkit (REPEAT), accessed October 2025; Jesse Jenkins, Jamil Farbes, and Ben Haley, *Impacts of the One Big Beautiful Bill on the US energy transition—summary report*, REPEAT Project, July 2025; Mark Chediak, “Trump’s tax law to cut U.S. clean-energy installs 41%, BNEF says,” Bloomberg, July 17, 2025; Ben King et al., “What passage of the ‘One Big Beautiful Bill’ means for US energy and the economy,” Rhodium Group, July 11, 2025; “OBBBA policy changes could reduce U.S. residential solar adoption by up to 46% through 2030—but massive long-term market potential remains,” Wood Mackenzie press release, August 4, 2025.

2 Ben Geman, “Trump rollbacks, vanishing tax credits to hammer U.S. EV sales,” Axios, June 18, 2025; and REPEAT, accessed October 2025.

3 *Global hydrogen review 2025*, IEA, September 2025.

4 *Pump it down: Why heat pump sales dropped in 2024—a country-by-country breakdown*, European Heat Pump Association, March 2025.

5 Climate Action Tracker for China, accessed October 2025.

6 Christian Therkelsen, Diego Hernandez Diaz, and Humayun Tai with Inés Ures, “How might tariffs affect the energy transition?,” McKinsey, July 22, 2025.

7 “Scaling bigger, faster, cheaper data centers with smarter designs,” McKinsey, August 1, 2025; and *Energy and AI*, IEA, April 2025.

8 “Big tech contracts inject life into new nuclear,” Reuters, February 19, 2025; “Elementl Power and Google sign strategic agreement to develop locations for advanced nuclear projects,” PR Newswire, May 7, 2025; and “XGS Energy and Meta to partner on 150 MW advanced geothermal project,” XGS Energy press release, September 2025.

9 Steven Nadel, *Opportunities to use energy efficiency and demand flexibility to reduce data center energy use and peak demand*, ACEEE, October 2025.

Consider hydrogen's two physical challenges—deploying hydrogen in an efficient way (challenge 20) and scaling hydrogen infrastructure (challenge 21). These have come up against significant headwinds. Cancellations of more than 50 hydrogen projects were announced from 2024 to mid-2025.[32] A wave of cancellations has also hit downstream projects reliant on hydrogen, including low-emissions steel projects (challenge 12) in Germany; ammonia production (challenge 15) in Australia; and more than 15 sustainable aviation fuel (SAF) projects for aviation (challenge 11).[33]

Having said this, there have been success stories even within Level 3. Better batteries and improvements in design, such as aerodynamics, have enabled electric trucks (challenge 9) to reach longer average ranges. Many original equipment manufacturers have extended the ranges of their flagship models, many of which can now travel more than 600 kilometers without recharging. The performance gap with diesel is narrowing. Battery electric trucks can now serve use cases that were previously thought to need low-emissions fuels such as hydrogen.[34] Furthermore, megawatt charging systems are offering faster charging than ever before. They could charge the average heavy-duty truck in about 15 minutes—half the time of an ultra-fast charging system.[35] The global stock of medium- and heavy-duty electric trucks more than tripled between 2022 and 2024. Still, they are at less than 1 percent of the 2050 target, and about 90 percent of them are in China.[36]

In heavy industry, cement has similarly bucked the trend. In 2025, the world's first full-scale cement carbon capture, utilization, and storage (CCUS) plant came online in Norway, and a pilot plasma-heated kiln came online in Sweden.[37] These were both milestones in tackling one of the toughest industrial decarbonization challenges.

Navigating the physical realities

The past two years have shown that the energy transition is moving in many directions at once. Some barriers are falling, while others seem to be getting taller. Overall, a nuanced understanding of the physical challenges and where there are headwinds and tailwinds remains critical for leaders looking to navigate the energy transition. (For details of all 25 physical challenges, see the appendix: "Progress report, 2024–25.")

Progress on what were already the Level 1 and 2 challenges has opened new opportunities. But making further headway will take more disciplined execution, both to maintain the pace of progress in challenges where it has been made and to accelerate where it hasn't. For business leaders, advantage will come from anticipating the next constraint and positioning early to remove it. The organizations most likely to succeed will be those that treat execution as a source of competitive advantage.

The hardest obstacles—Level 3 challenges—still depend on innovation, both in individual technologies and across entire systems. As our 2024 report discussed, it is essential to keep testing how technologies fit together within a wider system and how their roles may evolve. In the past two years, breakthroughs in low-emissions cement and electric trucks show that there is rarely a single route forward. For a long time, low-emissions fuels such as hydrogen were seen as the main way to match the performance of fossil fuels in these applications. Now denser batteries for trucks and electric and plasma-heated kilns for cement are pushing electrification ahead. Similar shifts could reshape other industries and open new paths to solving the demanding dozen.

Tackling the physical challenges of the energy transition remains hard stuff. There is progress but there are also headwinds. Building the capacity to read the landscape and act quickly on opportunities will matter more than ever. Clearly seeing the physical realities and how they change will help leaders steer toward lower emissions while ensuring an affordable, reliable, and competitive path to net zero.

Progress report, 2024–25

In this appendix, we outline progress on the 25 physical challenges since our 2024 report, classified by level of difficulty. We evaluate progress based on the balance of positive and negative developments. Of course, such an assessment is qualitative in nature; nonetheless, we believe the findings present a useful overview for decision-makers on areas of headwinds and tailwinds between 2024 and 2025.

We considered several dimensions: technological progress and advances in deployment, the impact of policy developments on the ability to solve physical challenges, and how well interdependencies are being addressed (for example, changes in the availability, cost, or readiness of inputs, build-out of support infrastructure, or the evolution of demand).[38] The overall trend is classified as positive (or negative) if at least two of these dimensions improved (or deteriorated) across the majority of the global asset base; otherwise, it is considered neutral.

Challenge	*Level*	*2024–25 trend*	*Assessment*
Power			
1. Managing renewables variability *Ensure sufficient supply-side flexibility in power systems*	3	Neutral	**Rapid expansion of batteries for short-term storage but limited progress in long-duration storage and grid expansion** • **Variability rose.** More deployment of solar and wind made power generation more variable, which among other factors led to increased curtailment and price volatility. In the UK, wind curtailment rates reached 8.5% in 2024, almost doubling from 2022. In Europe, the number of negative-price hours doubled.[39] • **Short-term storage advanced as costs fell about 20% in 2024.** This supported rapid growth in global storage capacity with capacity additions expected to double by 2025 versus 2023, led primarily by China. The decline in costs was driven by a combination of factors, including temporary oversupply due to battery manufacturing capacity overbuilds meeting slower EV demand, as well as structural improvements (eg, a shift from nickel manganese cobalt [NMC] to LFP chemistries and early commercialization of sodium ion batteries), lower minerals prices, and continued learning effects. Tech companies backed storage through solar-plus-storage power purchase agreements (eg, a 100-megawatt solar plant and a 300-megawatt solar-plus-storage deal in the US).[40] • **Long-duration energy storage (LDES) progressed only in a limited way.** Several projects came online in 2024–25, including a 200-megawatt facility in China and a 50-megawatt facility in Australia, along with new announcements and funding in Canada, Italy, and the US. Still, deployments remain few, relatively small scale, and early stage.[41] • **Bottlenecks remained in grid expansion.** Scaling transmission and distribution (T&D) networks was constrained by high materials input prices and regulatory hurdles such as permitting. This led to a 10% increase in renewable capacity waiting for grid connection globally, rising from 1.50 terawatts in 2023 to 1.65 terawatts in 2024. A shortage of skilled labor further threatens future expansion. Also see challenge 5.[42] • **Policy led to uneven effects.** In the US, tariffs have been a factor in contributing to increased battery costs, and reduced financial incentives for deployment from the OBBB Act could have further implications in the future. China relaxed storage mandates for renewables projects as it shifted to wholesale market trading.[43]

Challenge	Level	2024–25 trend	Assessment
Power			
2. Scaling emerging power systems *Ensure that power systems in emerging markets scale even while adding flexibility*	3	Neutral	**Emerging power systems continued to grow with a mix of renewable and fossil technologies** • **Investment increased, but international financing fell short of expectations.** Low-emissions energy investment in emerging economies excluding China reached about $2 trillion in 2024 globally, up about 65% from 2020. These economies now account for more than 40% of solar power additions; India's solar and wind deployment has grown by almost 80% since 2022.[44] However, international funding lagged. Just Energy Transition Partnerships delivered only $7 billion against a $50 billion target.[45] • **Distributed energy resources increased in pockets.** In Pakistan, for example, grid electricity sales fell about 10% as households adopted small-scale solar, highlighting the potential role of distributed solar in emerging markets and developing economies.[46] • **Fossil-fuel-related investment continued.** Investment into fossil-fuel power plants in China and other emerging market and developing economies (EMDEs) reached record highs in 2024. That investment is projected to continue to rise in China in 2025, while declining in other EMDEs.[47] • **Investment in flexibility options rose globally but remained limited in emerging economies.** Global investment in battery storage reached over $55 billion in 2024, almost 3 times the 2022 level, but only 4–6% was in emerging economies excluding China.[48]
3. Flexing power demand *Accelerate deployment of demand-side flexibility solutions*	2	Neutral	**Trials expanded, but deployment was limited** • **Demand-response programs increased but remain limited.** In the US, programs helped operators manage peak loads and avoid outages, while about 2 million customers enrolled in the United Kingdom's national demand flexibility program. New contractual models also emerged, such as time-based transportation discounts in the Netherlands. Still, overall deployment is limited.[49] • **New formats were trialed.** Data centers, utilities, and operators tested novel ways to make electricity demand more flexible. For example, workload choreography—implemented through AI training—shifted tasks across data centers or times of day to ease pressure during demand peaks.[50] • **Policy developments remained limited.** Some initiatives emerged, such as the EU's 2025 consultation on a new demand-response code, and some state-supported initiatives in the US.[51]
4. Securing land for renewables *Ensure there is enough land to deploy solar and wind*	2	Neutral	**Innovative land use models emerged, but bottlenecks persisted** • **Progress on efficiency.** New solar technologies (such as perovskite-silicon cells) pushed efficiencies to 25–30% in 2024–25, though deployment at scale has yet to follow. Onshore wind turbines also grew in height and rotor diameter, increasing by 2–5% in the US between 2023 and 2025.[52] • **New models for more efficient land use were trialed, but are still limited.** Several projects were launched globally to increase land-use efficiency, using multiuse models such as agrivoltaics or by developing low-value land such as desert areas and disused industrial sites.[53] • **Permitting accelerated but with limitations.** The US and EU streamlined some processes, but local restrictions persisted. About 450 US counties and municipalities imposed new restrictions, while in the EU the adoption of the Renewable Energy Directive (RED) III has been delayed in many member states.[54]

Challenge	Level	2024–25 trend	Assessment
5. Connecting through grid expansion *Expand the grid*	2	Mostly negative	**Grid investment rose but fell short of electricity demand and renewables expansion** • **T&D investments increased but remained below requirements.** Global grid spending rose to $390 billion in 2024, up almost 20% from 2022. Yet T&D investment lagged behind required spending to accommodate new renewable generation. This was one of the factors contributing to increases in solar and wind capacity awaiting connection. In high-income economies, aging infrastructure is adding to the need for modernization.[55] • **Supply chains became a tighter bottleneck.** Transformer and cable costs rose about 35% in 2022–24. Lead times roughly doubled to 2–3 years.[56] • **Long-range interconnections showed mixed progress.** For example, a planned line between Morocco and the UK was halted, while China completed two ultra-high-voltage lines spanning over 3,000 kilometers.[57]
6. Navigating nuclear and other clean firm energy *Accelerate deployment of clean firm energy*	2	Mostly positive	**Existing technologies accelerated, and support expanded for emerging ones** • **Growth in nuclear planned capacity.** Global nuclear power generation increased to 2,800 terawatt-hours in 2024, up 6% from 2022. This was driven by recovery in nuclear power output in France and Japan. While no significant capacity additions were made in 2022–24, new reactors are expected to become operational by the end of 2025 in China, India and South Korea. As of mid-2025, over 60 reactors were under construction, and about half were in China. Estimates vary, but these could add 24 to 34 gigawatts to China's nuclear capacity over the next decade, equivalent to a 40 to 65% increase from 2024 capacity.[58] • **Hydropower capacity stalled, but much is underway.** Global capacity stalled in 2022–24 with only a 3% increase in capacity of conventional and pumped storage hydropower combined, up 16 and 8 gigawatts, respectively, in 2024. Major projects came online in 2024 in China (14 gigawatts), Tanzania (almost 2 gigawatts), and Ethiopia (1.2 gigawatts). About 210 gigawatts of hydropower are under construction, the majority in China.[59] • **Pilots of new technologies progressed.** Construction of small modular reactors (SMRs) began, including in Argentina, China, Russia, and the US. Geothermal pilots also moved forward, including a 400-megawatt enhanced geothermal systems project in the US, expected to start in 2026. Lower drilling times (by as much as 80%) were achieved for geothermal technologies.[60] • **Demand for clean firm capacity surged in the US.** Major tech companies signed multiple power purchase agreements for data centers, including one to bring 500 megawatts online through SMRs by 2035, supporting the case for nuclear and geothermal development.[61] • **Policy backing for clean firm energy broadened.** Twenty-five countries now support tripling global nuclear capacity by 2050, with 6 joining at COP29 in 2024. A new World Bank–IAEA partnership was launched to expand nuclear capacity in emerging economies. In the United States, measures such as extended Inflation Reduction Act tax credits strengthened support for geothermal and streamlined approvals for early-stage projects, including advanced reactor designs.[62]
7. Driving BEVs beyond breakeven *Ensure that EVs have far lower lifetime emissions than ICEs*	1	Mostly positive	**Lower-emissions battery chemistries gained traction along with other tailwinds** • **Wider deployment of lower-emission batteries.** Share of lithium iron phosphate (LFP) chemistry in EV batteries increased to 50% in 2024—over 10 percentage points more than in 2022. LFP batteries are about 30% less carbon-intensive than NMC ones.[63] • **Battery recycling on an upward trajectory, driven by China.** Global recovery rates for cobalt, lithium, and nickel continued to rise. In 2024, China accounted for about 80% of global market capacity.[64] • **New battery recycling projects launched in the EU, but some setbacks occurred.** In 2024–25, some projects moved forward (Germany), while several projects in Spain and France were delayed or canceled.[65] • **Grid emissions decreased.** The global emissions intensity of electricity generation fell 1% in 2023 and 3% in 2024, reducing EV operating emissions.[66]

Challenge	Level	2024–25 trend	Assessment
8. Going the distance on BEV range *Ensure that EVs offer long enough range to satisfy consumer driving requirements*	1	Mostly positive	**Battery and charging technologies advanced** • **Progress in battery energy density.** Battery chemistries advanced significantly. About 10% higher energy density for sodium-ion batteries was achieved in 2025 vs 2023 models (achieving 175 watt-hours per kilogram). Lithium manganese iron phosphate (LMFP) batteries achieved 20% higher energy density than LFP. The first commercial launches of solid-state batteries occurred with 260 watt-hours per kilogram; demonstrations are targeting 400–500 watt-hours per kilogram.[67] • **Faster charging progressed.** In 2025, a new benchmark was set with the launch of passenger electric cars achieving a range of 400–500 kilometers in just 5 minutes of charging. These models support 1-megawatt charging (previously limited to heavy-duty vehicles with much larger batteries) and are now entering the passenger car market in China.[68] • **Battery swapping scaled up.** In China, new initiatives aimed for a total of about 30,000 battery-swapping stations, while projects were announced in Japan and Spain.[69]
9. Loading up electric trucks *Ensure electric trucks can carry heavy payloads over longer distances*	3	Mostly positive	**Advances in batteries and charging supported electric truck deployment** • **Battery energy density improved.** Higher-density batteries (challenge 8) enabled a wider number of original equipment manufacturers to produce truck models achieving 500–600 kilometers, increasing the average range reached by electric trucks.[70] • **Deployment increased but remained concentrated in China.** Sales grew about 80% in 2024, bringing the global stock to more than 400,000 electric trucks (0.5% of the total stock of all trucks), 90% of which are in China.[71] • **Charging optimized.** Megawatt charging systems are emerging for heavy-duty applications in China, the EU, and the US, enabling 15- to 30-minute charging. New business models also developed, including joint ventures and partnerships between automakers and utilities to expand high-power charging stations along key freight routes in Europe and the US.[72]
10. Charging up EVs *Expand battery capacity and charging infrastructure to support more EVs*	2	Mostly positive	**Charging technology and networks expanded** • **Charging networks expanded in line with EV growth.** Public charging points doubled in 2022–24, rising to 5.4 million, roughly matching the growth rate of EVs on the road. China installed almost 1.8 million public charging points in 2022–24 and had around 70% of the global stock of public charging points by the end of 2024.[73] • **Fast-charging systems grew most rapidly.** In 2024, public fast- and ultra-fast charging systems grew faster than slow ones, achieving almost 2 million units globally and more than doubling since 2022, with China responsible for 80% of the global growth.[74] • **Charging technology advanced rapidly.** Progress continued in charging technology in passenger cars as well as in heavy-duty vehicles.[75] • **Regulation was mixed.** The EU mandated charging points for commercial buildings under certain conditions; the US froze its $5 billion federal EV infrastructure program; India allocated $240 million to charging infrastructure in 2024, while new EV policies capped investments eligible for tariff relief.[76]

Challenge	Level	2024–25 trend	Assessment
11. Refueling aviation and shipping *Scale low-emissions fuels to decarbonize aviation and shipping*	3	Mostly negative	**Alternative fuels deployment remained limited** • **Production of sustainable aviation fuel (SAF) expanded but remained far below goals.** From 2022 to mid-2025, around 85 agreements have been signed. Although supply has tripled, SAF still accounted for only 0.3% of global jet fuel in 2024.[77] • **Deployment of new alternative-fuel facilities slowed worldwide.** Announcements fell, and several projects were canceled, including SAF facilities in Europe (Denmark, Germany, Netherlands, and Sweden) and hydrogen and ammonia projects in Australia.[78] • **Biofuel supply and infrastructure bottlenecks stalled shipping decarbonization.** By 2024, only about 2% of planned e-fuel projects for shipping had secured funding in the EU. Methanol gained traction, with rising orders for methanol-capable vessels and initial bunkering pilots, but scaling depends on expanding green molecule supply. Ammonia remained constrained by the absence of commercial bunkering infrastructure.[79] • **Policy developments are limited and mixed.** A vote on draft rules for the International Maritime Organization to mandate emission intensities by 2027 was adjourned for another year.[80] The US One Big Beautiful Bill Act reduced the tax credit rate for SAF, but extended its application period for two years to 2029.[81]
Industry			
12. Furnacing low-emissions steel *Decarbonize steel production with a range of new technologies*	3	Mostly negative	**Some technologies advanced, but overall progress was limited** • **Low-emissions steel investments stalled.** Market pressures curtailed new investments. Global overcapacity of about 600 million tons in 2024 (around 25% of existing capacity) suppressed prices of steel overall and reduced incentives for low-carbon steel technologies, especially given weakness in downstream sectors such as construction and automotive.[82] • **Hydrogen-based technologies faced setbacks.** Few new advances occurred in hydrogen-based direct reduced iron, and several projects were canceled, including in Germany and the US, due to challenging economics of hydrogen use in steelmaking.[83] • **Other low-emissions technologies advanced.** An industrial demonstration cell for molten oxide electrolysis was launched in the US, and a pilot for CCUS was trialed.[84]
13. Cementing change for construction *Decarbonize cement production with a range of new technologies*	3	Mostly positive	**Low-emissions cement advanced in pilots and first large-scale projects** • **Technology advanced in electrification, CCUS, as well as other pathways.** In Norway, the first full-scale cement CCUS facility came online. In Sweden, a plasma-heated electric kiln pilot achieved uninterrupted operation for 54 hours, and in Germany, an oxyfuel kiln CCUS project began. Additional CCUS projects were also launched elsewhere in the EU and in the UK. Universities pioneered alternative approaches such as clinker-free or recycled cements using electric processes, and new projects were announced using clinker substitutes in France, Switzerland, and the US. Biofuel use for heating also scaled, including projects in Uganda.[85] • **Policy development in China.** China, accounting for about half of global emissions for cement production as of 2023, approved an action plan to bring cement under its Emissions Trading System.[86] • **Increased use of alternative construction materials.** Alternative construction materials, such as wood, engineered wood products, or bamboo, gained traction. In the US, about 2,600 wood-based projects were in progress or built in mid-2025, 30% more than in 2023.[87]

Challenge	Level	2024–25 trend	Assessment
14. Cracking the challenge of plastics *Decarbonize plastics production with a range of new technologies*	3	Neutral	**Technologies advanced, but rollout and policy lagged** • **Technologies proved successful.** In 2024–25, large-scale demonstrations of electrically heated steam-cracking furnaces took place in Germany, and commercial-scale tests of hydrogen-fueled steam crackers advanced in the US.[88] • **Project rollouts faced challenges.** Progress in hydrogen-based processes slowed, with delayed investment in a hydrogen-fueled ethylene cracker in Canada, while chemical recycling also struggled, with several project cancellations or delays in the EU and the US in 2024–25.[89] • **Policy development was limited outside the EU.** The EU in 2025 adopted the Packaging and Packaging Waste Regulation, mandating higher recycled content and stronger recycling/reuse measures.[90]
15. Synthesizing low-emissions ammonia *Decarbonize ammonia production with a range of new technologies*	3	Mostly negative	**Setbacks confronted many electrolytic projects, but technologies progressed in carbon capture** • **Technological progress in blue ammonia.** A CCUS-equipped ammonia facility was launched in the US. In Northern Europe, new electrified steam methane reforming technologies are being tested; these remove furnace emissions and can simplify CO_2 capture.[91] • **Several projects in low-emissions ammonia were canceled.** Planned projects in Australia, Austria, Germany, and the US were shelved, both related to electrolytic and carbon capture routes in ammonia production.[92]
16. Heating other industries *Scale technologies to decarbonize other industries that use low-to-medium heat*	2	Mostly positive	**Technological progress and deployment continued, as policy and investor support grew** • **Deployment of low- and medium-heat technologies increased.** Industrial electric boiler sales grew another 10% in 2024, extending the recent trend.[93] • **Technological progress advanced.** Medium-size heat pumps can now reach higher temperatures, widening their market potential. The largest industrial heat battery to date (100 megawatt-hours) entered commercial operation in California. Progress in high-heat applications also continued, with new pilots in glassmaking, aluminum, and other sectors.[94] • **Support grew for thermal technologies.** Venture-capital funding for start-ups working on low-emissions heat technologies surged about 270% in 2024 while government backing strengthened. China launched an action plan to scale heat pump production; the EU's 2024 Net-Zero Industry Act eased permitting and investment support for heat pumps and thermal storage and launched funding for heat electrification; and Spain announced a €700 million program for energy storage.[95] • **Alternative forms of industrial heat progressed.** Geothermal advanced, along with other types of industrial heat, as new projects came online.[96]

<table>
<tr><th>Challenge</th><th>Level</th><th>2024–25 trend</th><th>Assessment</th></tr>
<tr><td colspan="4">Buildings</td></tr>
<tr><td>17. Facing the cold with heat pumps
Improve the performance of heat pumps in extreme cold</td><td>1</td><td>Neutral</td><td rowspan="2">Technology progressed while heat pump sales remained largely at 2022–23 levels
• Technology improved. New heat pumps for cold climates are nearing commercialization, able to deliver full capacity at –15°C without backup and at higher efficiency.[97]
• Sales were relatively stable globally. Global heat pump sales fell only 1% in 2024 after a surge in 2021–22 (driven by spiking gas prices at the time), and a small decrease between 2022 and 2023. China, the largest market, held steady, while the US grew about 15%. Meanwhile, EU sales dropped 21%, led by France and Germany, but remain above the 2021 level. Over a 5-year period adoption remained on an upward trend.[98]
• Policy support varied across regions. The EU as a whole promoted heat pumps and building electrification through its 2024 Energy Performance of Buildings Directive. The UK started a consultation on higher energy efficiency standards for privately rented homes. However incentive environments in the US, and some EU countries (eg, France, Germany, and Italy) were mixed. Programs moderated after earlier peaks, but many state or local incentives continued or expanded.[99]
• Slow T&D development increased future risks. Supply chain bottlenecks and longer lead times constrained the expansion of transmission and distribution networks (see challenges 1 and 5). Without accelerated T&D expansion, large-scale heat pump deployment could strain local grids in the coming years.[100]</td></tr>
<tr><td>18. Bracing for winter peaks
Manage power demand spikes from heating needs in cold weather</td><td>2</td><td>Neutral</td></tr>
<tr><td colspan="4">Raw materials</td></tr>
<tr><td>19. Unearthing critical minerals
Accelerate supply of critical minerals needed for low-emissions technologies</td><td>2</td><td>Mostly positive</td><td>Supply grew along with policy support
• Supply increased significantly. Global supply of key critical raw materials rose more than 20% on average in 2022–24. Supply of some materials grew much faster, with lithium up about 65% and cobalt up about 45%, while others were slower; copper supply grew just 5%.[101]
• Substitution progressed, reducing demand for some inputs. The global share of LFP chemistry batteries accounted for 50% of total batteries by the end of 2024, up more than 10 pp from 2022, reducing pressure on cobalt and nickel.[102]
• Policy support grew globally. The EU designated 60 strategic projects with faster permitting and financing to diversify supply and strengthen resilience. In the US, recent measures focused on expediting permitting, securing domestic processing capacity, and establishing partnerships across the world. Regulation and funding to boost mineral production expanded in Canada, China, and the UK.[103]
• New sources of demand could rise. AI is projected to increase demand. The IEA estimated that data centers powering AI could account for 2% of global demand for copper and silicon, 3% of rare earth elements, and up to 11% of gallium by the end of the decade.[104]</td></tr>
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Challenge	Level	2024–25 trend	Assessment
Hydrogen and other energy carriers			
20. Harnessing hydrogen *Ensure hydrogen is used in an energy-efficient way*	3	Mostly negative	**Deployment challenges persisted amid rising costs** • **Technology advanced, but pace remained slow.** There were advances in specific areas, such as solid oxide electrolyzer cells, efficiency gains in methane pyrolysis, and in low-iridium proton exchange membrane electrolysis. But overall technological development and deployment levels lagged behind projections. For instance, the IEA revised electrolyzer and hydrogen production costs up.[105] • **While more projects reached FIDs, progress was still very limited.** Investment in low-emissions hydrogen projects to reach FID more than doubled between 2022 and 2024, hitting $75 billion. Still, this was only 10% of announced investment in 2024.[106]
21. Scaling hydrogen's infrastructure *Scale infrastructure for the production, transport, and storage of hydrogen*	3	Mostly negative	• **Cancellations mounted in hydrogen and downstream sectors.** More than 50 hydrogen projects were canceled worldwide from 2024 to mid-2025. Additional cancellations occurred in downstream industries, including steel in Germany and ammonia production in Australia.[107] • **Pipelines and storage remained far below requirements.** Nearly 40,000 kilometers of new hydrogen pipelines were announced in 2024 for delivery by 2035, but only 2% reached FID. Planned hydrogen storage in 2024 amounted to just 1/20th of the 2035 requirement in the IEA Net Zero 2050 scenario at about 10 terawatt-hours, compared with 230 terawatt-hours.[108]
22. Managing biofuels footprint *Scale biofuels by managing land trade-offs*	2	Neutral	**Deployment increased, but there were no substantial developments to reduce pressure on land** • **Policies in key procuring countries promoted the role of biofuels.** In 2024, the EU expanded eligible feedstocks for aviation biofuels. In 2025, the US proposed higher blending targets, and Brazil raised mandates on ethanol and biodiesel blends, potentially increasing uptake, but also land use.[109] • **Global biofuels production increased.** Production rose 8% in 2024 and almost 20% in 2022–24, led by Brazil, China, and the US. In 2024, about 4.5 million tons of additional capacity became operational.[110] • **Project cancellations and limited technological progress hampered biofuel pathways that could reduce land use.** Several biofuel projects were canceled, and many focused on advanced biofuels with lower land requirements (eg, based on waste and residues). Third-generation biofuels (derived from algae and requiring no arable land) remained nascent and expected to remain limited in coming years. A rise of 10–20% in the price of waste oils to about $1,200 per ton in 2024 spurred demand for alternative cover crops (eg, winter canola) with their own land-use implications.[111]

Challenge	Level	2024–25 trend	Assessment
Carbon and energy reduction			
23. Expanding energy efficiency *Pursue a step change in the adoption of energy efficiency measures*	2	Neutral	**Gains occurred but were slow** • **Energy efficiency gains were slow and uneven.** Global energy efficiency, measured as primary energy intensity, rose just 1% in 2024, slowing from the pace in 2021–23 and falling well below the roughly 4% needed in net-zero scenarios. Gains were 2% in China, 0.6% in the EU, 1.5% in India, and 1.1% in the US.[112]
24. Capturing point-source carbon *Innovate new CCUS technologies and processes to make capture more effective and lower its cost*	3	Neutral	**Technology improved across CCUS phases, but deployment remained limited** • **Deployment remained limited.** Global carbon capture capacity increased substantially in 2024, with about 50% more capacity added, compared with 2022. Yet absolute levels remain very low, with global capacity just over 2 megatons of CO_2 vs a target of more than 1 gigaton by 2050.[113] • **Significant milestones were achieved in CCUS.** Several projects came on line in Australia, China, and the EU, including, in Norway, the first cement CCUS plant with an associated storage project; others reached FIDs or began construction, including in China, the EU, the UK, and the US. Offshore capture advanced in China, and major transportation and storage projects moved forward in Australia and Europe.[114] • **New uses for carbon are being piloted.** New pilot projects explored applications in construction and in the food industry.[115] • **Despite grant cancellations, some policy instruments have been expanded in the US.** In 2025, the administration canceled $3.7 billion in Department of Energy grants for more than 20 CCUS projects. However, the OBBB Act extended subsidies to carbon usage, including enhanced oil recovery.[116]
25. Capturing atmospheric carbon *Scale direct air capture*	3	Neutral	**Direct air capture (DAC) deployment remained very limited** • **New technologies improved.** New absorbent technologies were tested in the US. In Kenya, a first-of-a-kind geothermal-powered DAC project was tested.[117] • **Deployment remained very limited.** Global DAC capacity was only about 0.02 megaton in 2024, with no meaningful additions. The project pipeline of about 12 megatons was far below the 85 megatons needed by 2030 in the IEA's Net Zero scenario.[118] • **Cost projections worsened.** The largest DAC facility revised its cost projections upward. It still projects that costs will decline, but more slowly.[119]

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This is the latest publication in the McKinsey Global Institute's series on "the hard stuff", which explores the physical challenges that need to be tackled for a successful transition from a high-emissions to a low-emissions energy system. This research takes stock of progress on the energy transition across the full range of physical challenges. As with other research in the series, we collaborated closely with McKinsey's Global Energy and Materials Practice and McKinsey Sustainability.

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